ELSEVIER

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Energy Procedia 37 (2013) 5994– 6001

Energy Procedia

GHGT-11

Storage Potential and Economic Feasibility for CO_2 Micro-bubble Storage (CMS) in Japan

Takumi Shidahara [a]*, Tadahiko Okumura [b], Hideaki Miida [b], Masato Shimoyama [c], Norifumi Matsushita [d], Takashi Yamamoto [e], Takeshi Sasakura [f], Toyokazu Ogawa [g]

[a] *NEWJEC Inc., 12-13, Shin ohashi 1-chome, Koto-ku, Tokyo, 135-0007, Japan*
(former Central Research Institute of Electric Power Industry (CRIEPI), Japan)
[b] *Engineering Advancement Association of Japan (ENAA), 3-18-29, Toranomon, Minato-ku, Tokyo, 105-0001, Japan*
[c] *Obayashi Corporation, 4-640, Shimokiyoto, Kiyose-shi, Tokyo, 204-8558, Japan*
[d] *Oyo Corporation, 2-2-19 Daitakubo, Minami-ku Saitama-shi, Saitama, 336-0015, Japan*
[e] *Kawasaki Geological Engineering Co. Ltd, 2-11-15, Mita, Minato-ku, Tokyo, 108-8337, Japan*
[f] *Kajima Corporation, 2-19-1 Tobitakyu, Chofu-shi Tokyo, 182-0036, Japan*
[g] *Taisei Corporation, 344-1 Nasecho, Totsuka-ku, Yokohama-shi, Kanagawa, 245-0051, Japan*

Abstract

Although CO_2 underground geological storage has been proposed, it is important for smaller emission sources to develop a local and distributed small-scale CO_2 underground storage system, too. To examine if it is feasible, CO_2 micro-bubble storage (CMS) as one of the small-scale systems has been studied. As part of this ongoing study, the following two subjects were examined: 1) geological conditions appropriate to the CMS and its storage potential in Japan; and 2) outline cost estimation of the CMS. Results of this study showed that the CMS system could well be feasible technically and economically.

Keywords; Underground geological storage, CO_2 micro-bubble, Dissolution, Small-scale emission source, Small-scale distributed storage, Storage potential, Economical evaluation

1. Introduction

As one of the measures against global warming, CO_2 underground geological storage (CO_2 capture and storage: CCS) has been proposed. Currently the CO_2 storage in deep saline aquifers greater than 800m in

* Corresponding author. Tel.: +81-3-5625-1806; fax: +81-3-5625-1870.
E-mail address: shidaharatk@newjec.co.jp.

doi:10.1016/j.egypro.2013.06.527

depth seems most popular. Although CO_2 can be effectively stored in a dense state in this system, it must be sealed by a cap rock, as a sealing layer to prevent CO_2 plume from migrating upward by buoyancy. The system generally expects storage of CO_2 in the order of 1 Mt-CO_2 per annum.

Unlike such large-scale underground storage systems, termed large scale concentrated CCS here after, it is important for smaller emission sources such as hydrogen production plants in oil refineries or chemical plants to develop a small but more effective storage scheme in distributed locations to be able to minimize storage and transportation costs easily, *e.g.*, by making sinks come close to sources. To examine if it is feasible, CO_2 micro-bubble storage, termed CMS hereafter, has been studied as a local and distributed small-sized CO_2 underground geological storage system [1)]. In CMS, CO_2 micro-bubbles are generated to obtain immediate and effective dissolution into water, and the CO_2 dissolved water is injected underground.

As part of this ongoing study, the results of the following two subjects are presented in this paper: 1) examination of the geological conditions appropriate to the CMS and its storage potential in Japan; and 2) outline cost estimation of the CMS.

2. Storage potential

2.1. Geological condition appropriated for CMS

CO_2 dissolved water is slightly heavier than groundwater, and the chance for CO_2 to migrate upward is small. It is therefore possible to store CO_2 safely at shallower depths, as long as groundwater is not domestically used. The storage unit designed in CMS is composed of an injection well of CO_2 at the center and 4 circumferential wells for pumping up groundwater to be used to dissolve CO_2 (Hitomi et al. (2012)) [2)].

Taking the above concept of CMS system into consideration, the following geological conditions have been specified as examination criteria:

1) Presence of sealing layer as a caprock for greater safety;
2) Presence of a highly permeable porous reservoir (*e.g.*, sandstone) and an impermeable layer of low porosity as a caprock (*e.g.*, mudstone) in the sedimentary basin; and
3) Distribution of Neogene to Quaternary Pleistocene sedimentary rocks at depths between 300 and 500 m.

There are a number of sedimentary basins containing Neogene to Quaternary Pleistocene sedimentary rocks in the coastal areas of Japan. In this study 11 sedimentary basins are selected from those studied by RITE / ENAA (2009) [3)], including Sothern of Hokkaido, Japan Sea near the coast of Akita, Tokyo Bay, Ise Bay, Osaka Bay, Northern and southern Kyushu and the southern part of Okinawa Island, as probable promising areas by the existence of sedimentary basins and emission sources (Fig. 1.). The storage feasibility of the 11 basins was then evaluated on the basis of their geological stratigraphy, rock facies, geological structures and emission sources (Table 1.). Overall three sedimentary basins, including Boso Peninsula, Osaka Bay, and Okinawa, were found more promising than the others. When additional geological data become available, or caprock layer is proven unnecessary, the number of appropriate basins would increase, since almost all of the stored CO_2 is kept in dissolution.

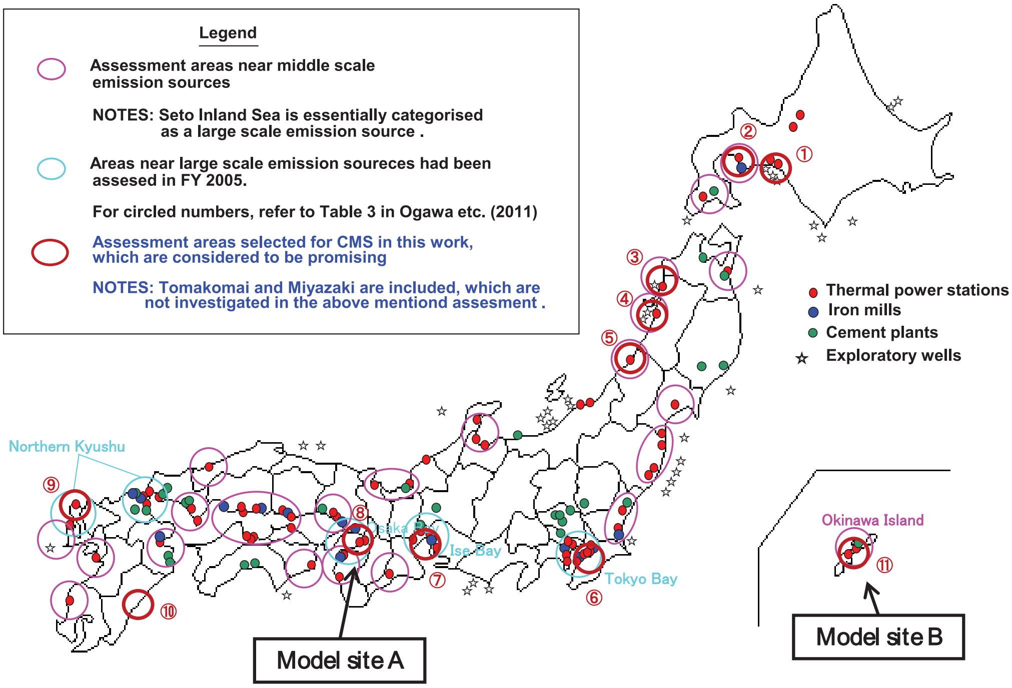

Fig. 1. Locations of emission sources and possible promising sedimentary basins considered for CMS in Japan (quoted from Ogawa et al. (2011) and partly modified) [4])

2.2. Storage potential

Among the 11 basins, feasibility of the CMS units was tested at 2 locations (model site A, B) selected from a type of emission sources and the above geological property, and at depths between 300 and 500m (only in the vicinity of a plant in the site B), storage potentials of 152, and 2.4Mt-CO_2 were estimated, respectively.

Possible quantity of storage is estimated by the procedure shown below [1]).

$$\textit{Possible Quantity of Storage} = Rc \times A \times h \times \quad \times CO_2 \textit{ concentration} \qquad (1)$$

Rc: Reduction coefficient in consideration of the uncertainty arising from the injection of CO_2 dissolved water, accuracy of geological survey and inhomogeneity of geology, and so on. (assumed 0.25)

A: Area of storage aquifer

H: Effective thickness of storage aquifer

: Porosity of storage aquifer

CO_2 concentration: (= 0.04t/m^3H_2O)

CO_2 concentration is estimated from the pressure and temperature conditions when CO_2 is stored at the depth of 400meters below the sea level.

Table.1 Investigation results of promising sedimentary basins for CMS in Japan (quoted from ENAA GEC (2012) [1])

	Area of interest[*1]	Target geological formations[*2]	Geological characteristics						Geological structures			Emission sources	
			Caprock			Storage aquifer							
			Continuity	Imperviousness[*3]	Strength[*4]	High porosity	High permeability	Homogeneity	Combination of caprock and storage aquifer		Active structure (folds, faults) Not close to active volcanos	Storage aquifer present in the vicinity	Small-scale emission source present (0.1Mt-CO_2/yr)
1	Tomakomai	Quaternary to tertiary sedimentary rocks	△	○	△	○	○	○	○	CR: saphenous marine Pleistocene series (silt, peat) AQ: saphenous marine Pleistocene series (sand, sandy gravel)	×	○	○
2	Muroran	Quaternary to tertiary volcanic rocks	×	△	△	△	△	×	△	CR: uppr Rumoi formation AQ: lower Rumoi formation	×	○	○
3	Noshiro	Tertiary sedimentary rocks	○	○	△	○	○	○	○	CR: Sasaoka formation AQ: Tentokuji formation	×	△	△
4	Akita	Tertiary sedimentary rocks	○	○	△	○	○	○	○	CR: Sasaoka formation AQ: Tentokuji formation	×	○	○
5	Shonai	Quaternary Pleistocene Series	○	○	△	○	○	○	○	CR: Sasaoka formation AQ: Jozenji formation	△	△	△
6	Boso peninsula	Middle Kazusa Group. (mainly Otadai formation and upper formations)	○	○	△	○	○	○	○	CR: AQ: Middle Kazusa Group	○	○	○
7	Ise Bay	Owari Grop, Tokai Group (Yoneno formation)	○	○	△	○	○	○	○	CR: Yoneno formation AQ: Oizumi formation & lower formations	△	○	○
8	Osaka Bay	Lower Osaka Group	○	○	△	○	○	○	○	CR: marine clay Ma3 to Ma-1 AQ: sand layers below Ma3	○	○	◎
9	Matsuura	Paleogene sedimentary rocks	○	○	○	△	△	△	○	CR: fine facies in Sasebo Group AQ: coarse facies in Sasebo Group	△	○	△
10	Miyazaki	Tertiary sedimentary rocks	○	○	○	○	○	○	○	CR: upper Miyazaki Group AQ: lower Miyazaki Group	○	△	△
11	Okinawa	Tertiary sedimentary rocks	○	○	○	○	○	○	○	CR: Yonabaru formation AQ: Tomigusuku formation	○	○	◎

Notes: *1 Eleven locations extracted from the presence of sedimentary basin and the location of emission sources
*2 Formation considered to distribute 300 to 500 m underneath emission sources (mainly coastal and plain areas)
*3 Few tight cracks with extremely low permeability (< 10^{-9} m/sec)
*4 Strength larger than the sum of one equivalent to desired depth and injection pressure that will not trigger failure.

Legends:

CR: caprock	○	suitable
AQ: aquifer	△	somewhat suitable
	×	not suitable

At model site B, sandstone layers which are targeted for storing CO_2 are distributed under the land area and sea area at and near the oil refinery plant, where they gently dip to the sea. It was possible to set the storage area in the range of around 2km × 4km in the land and front sea area of the plant (Fig. 2.). For the sandstone aquifer, thickness was assumed 100m in the range of 300m to 500m in depth (Fig. 3.). Under these conditions, that storage area is 2,000 × 4,000m^2 in plane, effective thickness is 100m, and porosity is 0.3, amounting to a possible storage capacity of 2.4Mt-CO_2.

If an injection pressure smaller than 1MPa (low enough not to damage reservoir nor seal layer) is applied, an annual injection rate of 10 thousand t-CO_2 per year is adequately feasible. Since the calculated maximum potential is 150 thousand t-CO_2 per a storage unit, two units may be adequate for a storage period of more than 15 but less than 30 years (Hitomi et al. (2012)) [2]. It may be noted that an annual storage amount may be increased by increasing the number of units. It appears that the system is technically feasible.

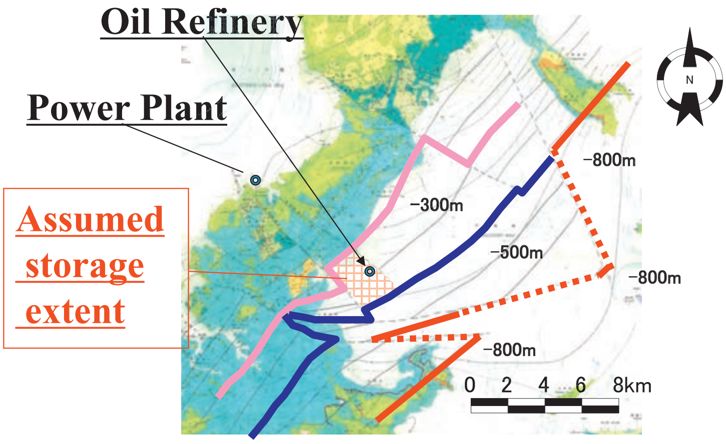

Fig. 2. Assumed storage area of the model site B on the plane (quoted from GSJ (1987) [5] and partly modified) [1]

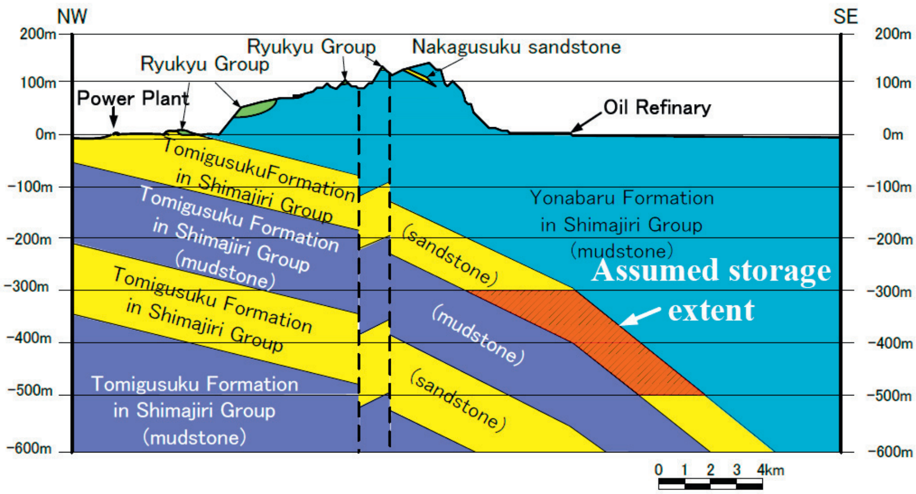

Fig. 3. Assumed geological cross section and storage area of the model site B (quoted from ENAA GEC (2012) [1])

3. Economical evaluation

Cost evaluation of the CMS system was carried out, taking construction cost of the storage unit facilities into account. Basic storage unit is comprised of 1-500m long injection well, 4-500m long circumferential wells, CO_2 and groundwater transportation pipelines, compressor for micro-bubble generation on the ground, pumps on the ground and so on. The distance between the injection well and a circumferential well, *viz*., the unit radius is set at 200m.

The following assumptions were made for the cost evaluation:

- Pure CO_2 is given from the emission source. Separation and capture cost are not included.
- CO_2 micro-bubble is generated in the underground.
- Pipeline length is short from the emission source to the injection well.

Under these conditions, storage cost excluding separation and capture cost was estimated to be about JPY4,600 to 6,100/t-CO_2 (Table 2.). In trial calculation of CMS, drilling cost, well logging cost, monitoring cost, maintenance cost and transportation cost were set and calculated and added up. They were calculated in the 2 cases as shown in the Fig. 4., where one is with an annual injection rate of 10 thousand t-CO_2 per year and the other is with rate of 20 thousand t-CO_2 per year. In this calculation, storage period for one unit was assumed to be 20 years, and the costs of a compressor and the pumps were not added because it was thought that it was small. Although equipment cost of large-scale concentrated CCS is cheaper than CMS because there is scale effect, total cost for the CMS excluding separation and capture cost will become cheaper than large-scale concentrated CCS when transportation cost is considered. Rational arrangement of the wells for injection and pumping in storage units may further lead to a lower storage cost in the CMS system.

Furthermore, contribution of CMS to CO_2 reduction was compared with those by the large-scale concentrated CCS or generation of the renewable energy on a basis of a preliminary cost calculation result for the CMS. In this case, generation cost of the renewable energy which provides the same amount was found, based on quantity of generation in 1t-CO_2 exhausted from the oil fired power station (1,420kWh for a discharge coefficient of 0.704kg-CO_2/kWh [6)]). The generation unit price by renewable energy were quoted from the maximum values in Energy white paper (2008) [7)] and the report of energy, environmental strategy meeting (2011) [8)]. The selling of generation unit price of the renewable energy was uniformly reduced from generation unit price by JPY25/kWh. CO_2 reduction effect in the CMS is higher than solar power generation, micro hydro power generation and biomass generation, but is less than geothermal generation and wind power generation (Fig. 5.). However this comparison depends on the selling of generation unit price of the renewable energy. In addition, the cost of large-scale concentrated CCS was quoted from the estimation by RITE (2007) [9)], in which 1 Mt-CO_2/y was separated and captured from domestic new coal fired power station and transported for a distance of 20km and stored. The separation and capture cost are not included in CMS because of pure CO_2 given from the emission source. Although the total cost of CMS becomes higher than large-scale concentrated CCS when the capturing cost of large-scale concentrated CCS is just added, the cost increase is not so big.

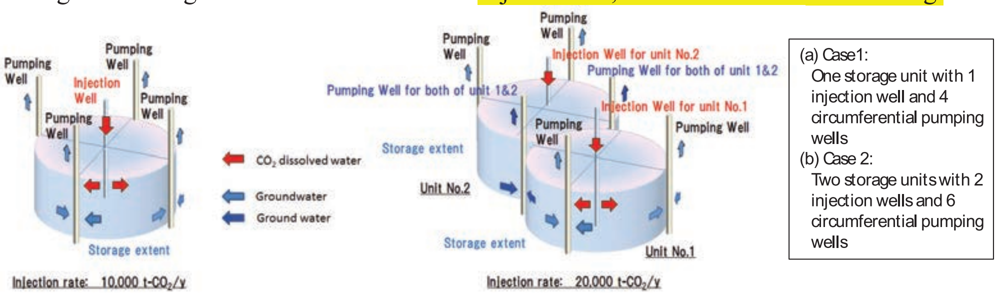

Fig. 4. **Concept of storage unit for trial calculation (Left: Case1, Right: Case2)**

Table.2 Trial calculations of the total cost for CMS (quoted from ENAA GEC (2012) [1])

Drilling cost, monitoring cost, maintenance and management cost

Expenditure Item	Case 1	Case 2	Remarks
Injection rate (t-CO_2 / y)	10,000	20,000	Refer to Fig.4. A radius of 1 storage unit is 200m.
No. of injection wells	1	2	
No. of pumping wells	4	6	
Total amount of injection (t-CO_2 / 20yrs)	0.2 M	0.4 M	
Well logging			
Total well length (no. x m)	5 x 500 = 2,500 m	7 x 500 = 3,500 m	
Injection system			Equipment cost = Equipment expense x 0.13 / injection rate. 10% of equipment expense as 15 yr depreciation + 3% of equipment expense as maintenance cost = 13%
Injection well (1 x 500m)	JPY 78 M	JPY 78 M x 2	
Pumping well (4 x 500m)	JPY 78 M x 4	JPY 78 M x 6	
Total equipment cost	JPY 390 M	JPY 620 M	
Equipment cost / t-CO_2	JPY5,070 / t-CO_2	JPY4,056 / t-CO_2	
Monitoring			5 surveys Operation cost = (survey cost / 20 yrs) / injection rate
2D reflection survey	JPY 50 M	JPY 50 M	
Automatic measurements in pumping well	JPY 50 M	JPY 50 M	
Operation cost	JPY50/t-CO_2	JPY50 / t-CO_2	
Totals	JPY 490M JPY5,120 / t-CO_2	JPY 670M JPY4,106 / t-CO_2	

Total cost for CMS

Expenditure Item	Case 1	Case 2	Remarks
Drilling / monitoring / maitenance / management	JPY 490M JPY5,120 / t-CO_2	JPY 670M JPY4,100 /t-CO_2	
Transportation cost Pipeline	JPY 10M JPY1,000 / t-CO_2	JPY 10M JPY500 / t-CO_2	
Totals	JPY6,120 / t-CO_2 (JPY9,120 / t-CO_2)*	JPY4,606 / t-CO_2 (JPY7,606 / t-CO_2)*	Figures in brackets are values under an assumption that the capturing cost is JPY 3,000 / t-CO_2.

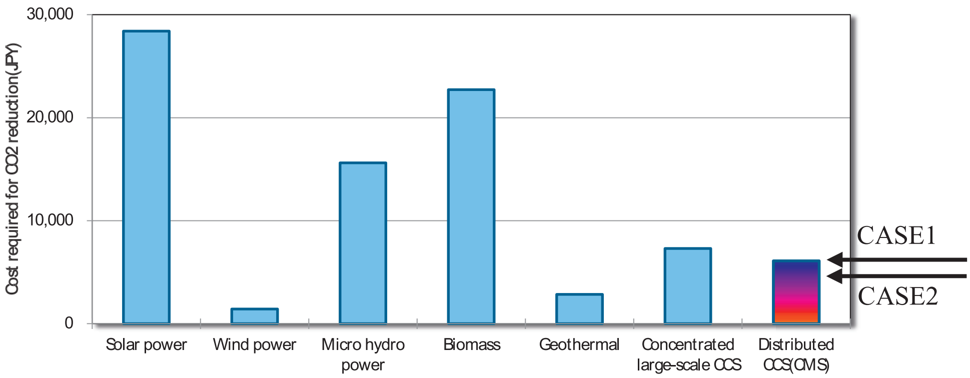

Fig. 5. Cost required for the reduction for 1 ton-CO_2 emission based on (maximum) generation unit price (quoted from ENAA GEC (2012) [1])

4. Summary and Conclusions

As part of this ongoing study, geological conditions appropriate to the CMS and its storage potential in Japan were examined, and outline cost estimation of the CMS was carried out.

From the results of the study, CMS was found to be suitable as a local and distributed small-sized CO_2 underground storage system, for smaller emission sources such as hydrogen production plants in oil refineries and other small-scale emission sources which emits the highly concentrated CO_2. For practical use, additional investigations, such as an effective method of CO_2 micro bubble generation in the underground, environmental assessment and monitoring, are still remained. They are going to be carried out in the near future.

Acknowledgements

The authors are indebted to the JKA Foundation for financially supporting this study with a subsidy of Keirin. This study was carried out by General Incorporated ENAA Foundation.

References

[1] Engineering Advancement Association of Japan, Geo-space Engineering Center (ENAA GEC). Report about the fiscal year 2011 research on feasibility of the CO_2 micro-bubble underground storage, ENAA GEC 2011-P2; 2012 (in Japanese)

[2] Hitomi, T., Sasakura, T., Yamaura M, Tozawa, M., Tagami, M., Suzuki, K., and Wada, H. Numerical analysis of storage potentials for CO_2 micro-bubble storage (CMS), GHGT-11; 2012

[3] Research Institute of Innovative Technology for the Earth (RITE)/ENAA. Research development on carbon dioxide underground storage technology, quantity of storage aquifer existence investigation in Japan, Data base of investigation results; 2009 (in Japanese)

[4] Ogawa T., Nakanishi S., Shidahara T., Okumura T., Hayashi E. Saline-aquifer CO_2 sequestration in Japan-methodology of storage capacity assessment, *International Journal of Greenhouse Gas Control 5*, 318–326; 2011

[5] Geological Survey of Japan (GSJ). Japanese oil field, gas field figure 12, Okinawa Island middle southern district; 1987 (in Japanese)

[6] Environmental Information Center. Environmental Information & Communication Network, Environment Q&A, No.823; 2002 http://www.eic.or.jp/qa/?act=view&serial=822 (in Japanese)

[7] Ministry of economy, trade and industry (METI). Fiscal year 2007 annual report about energy (energy white paper 2008); 2008 (in Japanese)

[8] Energy, environmental meeting, Inspection Committee such as cost. Report of an inspection committee such as cost, Reference materials 2 test calculation list of generation cost; 2011 (in Japanese)

[9] Takagi M. An economy evaluation and the effectiveness of the underground storage in Japan. *2007 RITE CCS workshop* documents; 2007 (in Japanese)